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Intense Proton Beam Plasma Interactions

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Abstract

A study has been initiated to investigate interactions between an intense proton beam and a background hydrogen plasma. The magnetic and electric neutralization of the ion beam by the plasma as well as collective interactions between the beam and the plasma are objects of this study. The plasma is produced by a conical theta-pinch gun and injected into a 2 kG solenoidal guide field. Plasma densities in the neighborhood of 10^{10} cm^{-3} and electron temperatures of a 1-3 eV can be produced by careful operation of the plasma gun. The plasma column is 60 cm long and 2 cm in diameter. A 20 A/cm^2 proton beam is emitted from a magnetically insulated diode at 400 keV and injected axially into the plasma column. This paper presents a description of the experiment and some initial experimental results.

Introduction

To study the interactions between an intense proton beam and background plasma a pulsed beam-plasma experiment has been constructed. To best observe and analyze the beam-plasma interactions the following experimental conditions were produced:

1. A reproducible, cold, low density, highly ionized plasma.

2. A reproducible proton beam of approximately the same density as the plasma, traveling with an axial velocity much greater than the plasma thermal velocity.

3. The radial extent of the plasma is much greater than V_{beam}/ω_{plasma} so the collective interaction can be analyzed with a 1-d model.

4. The interaction region for the beam plasma system is sufficiently long to observe the interaction of interest.

Apparatus

The plasma source is shown in Fig. 1 and is built around a 140 cm long, 7.6 cm inner diameter Pyrex tube. The tube is evacuated to 10^{-6} Torr with a cold trapped diffusion pump.

At one end of the tube is a 24 turn, 60 cm long, 18 cm diameter, guide field solenoid. A 208 μf capacitor bank charged to 2 kV is discharged through an ignitron into the 30.5 μh solenoid with a period of 510 μs. At the end of the first quarter cycle a second ignitron crowbars the capacitor, causing current in the solenoid to flow with a L/R decay of 3 ms. The resulting axial magnetic field has a magnitude of 2 kG and is uniform to within 10% over the central 41 cm.

On the opposite end of the Pyrex tube is a magnetically driven fast acting puff valve. The field coil of the puff valve consists of 20 turns wrapped on a 3 cm long, 2.1 cm diameter slotted copper cylinder with a 0.64 cm hole drilled along the axis. On one end of this copper flux excluder an "O" ring is seated with a 0.1 cm thick, 2.3 cm diameter, 1.12 gm aluminum disc held against it with a spring. The spring has a constant of 1.2 x 10^4 Kg/s^2, weighs 6 gm, and is compressed enough to maintain a good vacuum seal for plenum pressures up to 14 lb. The plenum has a volume of 2 cc and is normally operated at a pressure of 1 lb.

A 4 μf capacitor, charged to 6 kV is discharged through an ignitron into the 2.5 μh field coil with a period of 20 μs. The magnetic field created causes eddy currents to flow in the aluminum disc. A mutual repulsion results, forcing the disc from the "O" ring, admitting hydrogen into the evacuated Pyrex tube. Approximately one-half of the plenum gas is emitted during the time the valve is open which is estimated to be a few microseconds.

Pressure measurements were made in the Pyrex tube, at the center of the conical θ-pinch, with a fast ionization gauge. The pressure rose to approximately 900 mT in 185 μs.

Located next to the puff valve is a 3 turn conical θ-pinch coil. The inner diameters at the ends of the 10.4 cm long coil are, 9.9 cm and 13.95 cm, giving a taper of 11°. A 1.94 μf capacitor, charged to 12 kV, is discharged through a spark gap switch into the 521 nh θ-pinch coil with a period of 6.8 μs. An external inductance of about 80 nh is mainly located in the spark-gap switch and the capacitor. At the end of the third quarter cycle the capacitor is crowbarred, with an ignitron, causing current to flow in the θ-pinch coil with a L/R decay of 0.3 ms.

The electric field in the θ-direction caused by the axial dB/dt creates a plasma discharge in the hydrogen admitted to the system by the puff valve. No measurable plasma is formed during the first quarter cycle and this is believed to be a preionization phase. The bulk of the plasma is formed between the second and third quarter cycles.

The discharge is initiated near the inner wall of the Pyrex tube, forming a cylindrical diamagnetic current shell which carries current in a direction opposite to the current flow in the θ-pinch coil. The current in the plasma interacts with the radial and axial magnetic fields created by the increasing current flow in the conical θ-pinch. Computer simulation of the magnetic fields in the θ-pinch coil yield an axial field strength of 0.1 Kg/Ka, at the center of the coil.

The radial $J_\theta \times B_z$ force collapses the cylindrical plasma shell on axis. A fraction of the neutral hydrogen atoms which collide with collapsing shell are ionized and "snowplowed" towards the axis. The axial $J_\theta \times B_r$ force ejects the plasma down the Pyrex tube with a velocity of approximately 2.2 cm/μs.

The plasma enters the guide field and is magnetically confined in a 60 cm column of 1 cm radius. Floating double Langmuir probe measurements give a peak density of 10^{10} cm^{-3}, temperature of approximately 1-3 eV, and a duration of several hundred microseconds.

The proton beam is produced by a racetrack type magnetically insulated diode. (shown in Fig. 2) The diode is driven by the 0.1 kJ, 3 Ω Castor generator, in the 100 ns pulse configuration.

The cathode serves as a one turn insulating field coil. A 200 μf capacitor is charged to 7 kV and discharged through an ignitron into the

450 nh insulating field coil with a 59.6 μs period. This produces a peak insulating magnetic field of 12.7 kG in the 4 mm A-K gap, giving a B/B_{crit} of 3.1.

The magnetic field generated in the A-K gap suppresses electron flow across the gap. This allows a greater fraction of the total current to be carried by protons. The protons are accelerated across the A-K gap to an energy of 400 keV and exit the diode at 10^7 m/s. The insulating magnetic field deflects the protons approximately 3° from straight line trajectories.

The proton source is a 0.15 cm thick, 10.16 cm x 12.7 cm, polyethylene sheet mounted on the anode. The polyethylene is drilled with 0.5 mm diam holes, spaced 0.25 cm apart, to enhance anode plasma formation. A beam of approximately 80% protons and 20% carbon is formed by this anode material.

An 11.5 cm diameter, cylindrical, beam is extracted through slots in the cathode and a cylindrical flux excluder. The beam is charge neutralized by electrons which are either pulled from the cathode sheath or are emitted from the bombarded cathode vanes. The flux excluder keeps the insulating magnetic field away from the back of the cathode to optimize the neutralization process.

A large biased charge collector measured an average current density of 20 A/cm at a distance of 20 cm from the diode. This is in good agreement with the Child-Langmuir calculated proton current density. Oscillograms taken during the operation of the experiment are shown in Fig. 3.

Operation

The sequence of events during a shot is as follows. First the guide field is errected creating an essentially static magnetic field for the lifetime of the plasma. At the same time the guide field is crowbarred the puff valve is fired allowing hydrogengas to enter the system. After 185 μs the front of the hydrogen gas puff has traveled about 19 cm down the tube but has not yet reached the guide field region. The conical θ-pinch is then fired ejecting a plasma puff of approximately the same length as the θ-pinch coil down the tube, beating the neutral hydrogen puff to the guide field region. This sequence of events is crucial to produce the low density plasma.

As the plasma puff passes through the neutral hydrogen a number of effects are observed. The plasma density drops from approximately 10^{13} cm^{-3} at the conical θ-pinch to 10^{10} cm^{-3} in the guide field region. The plasma puff expands in length to completely fill the guide field region. Shot to shot reproducibility is greatly increased. And a second plasma puff, moving at the velocity of the neutral hydrogen gas puff, is formed.

When the plasma has filled the guide field region but hasn't reached the diode region the proton beam is fired axially into the plasma. Net current measurement will be made in the guide field region to study current neutralization of the beam by the plasma. Observation of the emitted rf spectrum will be used to identify collective two-stream interactions between the proton beam-plasma system and the co-moving electrons-plasma system.

Acknowledgements

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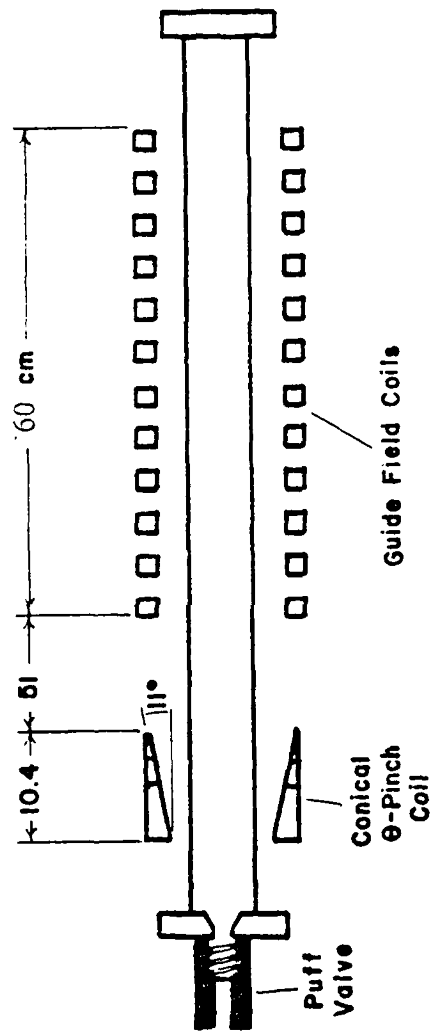

Fig. 1 Plasma source.

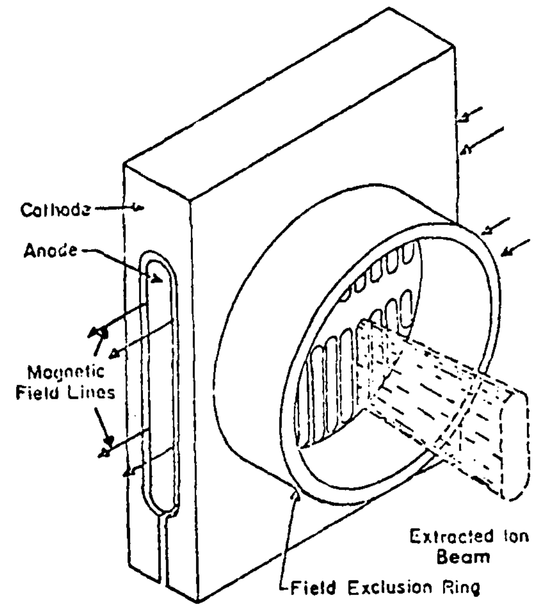

Fig. 2 Magnetically insulated racetrack diode.

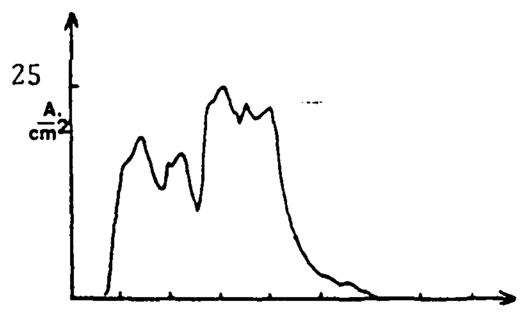

Fig. 3b Ion current density 100 ns/div.

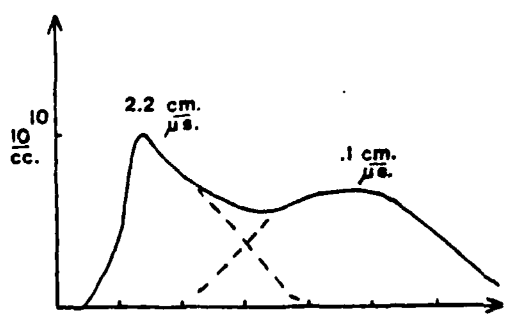

Fig. 3a Plasma density 100 μs/div.

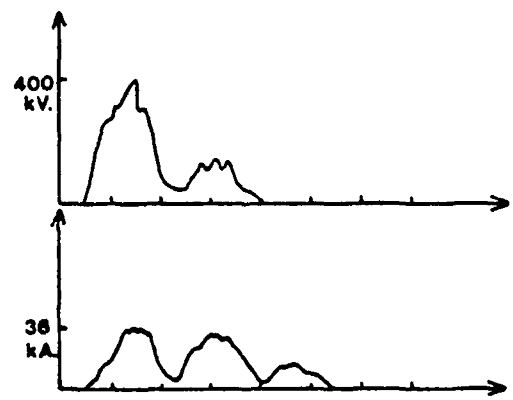

Fig. 3c Top: Diode voltage 100 ns/div.
Bottom: Diode current 100 ns/div.